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Insulated Power Cables Used in Underground Applications

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Aesthetics is primarily the major reason for installing power cables underground, providing open views of the landscape free of poles and wires. One could also argue that underground lines are more reliable than overhead lines as they are not susceptible to weather and tree caused outages, common to overhead power lines. This is particularly true of temporary outages caused by wind, which represents approximately 80% of all outages occurring on overhead systems. However, underground lines are susceptible to being damaged by excavations (reason behind “call before digging” locating programs implemented by many states in the U.S.). The time required to repair a damaged underground line may be considerably longer than an overhead line. Underground lines are typically ten times more expensive to install than overhead lines. The ampacity, current carrying capacity, of an underground line is less than an equivalent sized overhead line. Underground lines require a higher degree of planning than overhead, because it is costly to add or change facilities in an existing system. Underground cables do not have an infinite life, because the dielectric insulation is subjected to aging; therefore, systems should be designed with future replacement or repair as a consideration.

12.1 Underground System Designs

There are two types of underground systems (Fig. 12.1).

- A. Radial—where the transformers are served from a single source.
- B. Looped—where the transformers are capable of being served from one of two sources. During normal operation an open is located at one of the transformers, usually the midpoint.

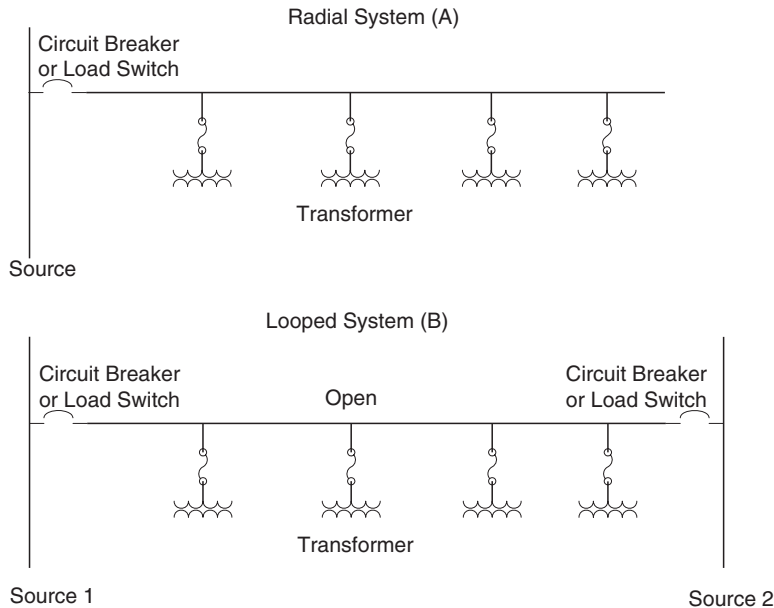


FIGURE 12.1 (A) Radial system and (B) looped system.

A radial system has the lowest initial cost, because a looped system requires the additional facilities to the second source. Outage restoration on a radial system requires either a cable repair or replacement, whereas on a looped system, switching to the alternate source is all that is required.

Underground cable can be directly buried in earth, which is the lowest initial cost, allows splicing at the point of failure as a repair option and allows for maximum ampacity. Cables may also be installed in conduit, which is an additional cost, requires replacement of a complete section as the repair option, reduces the ampacity, because the conduit wall and surrounding air are additional thermal resistances, but provides protection to the cable.

Underground power cables have three classifications.

1. Low voltage—limited to 2 kV. Primarily used as service cables
2. Medium voltage—2–46 kV. Primarily used to supply distribution transformers
3. High voltage—above 46 kV. Primarily used to supply substation transformers

American Standards Testing Material (ASTM), Insulated Cable Engineering Association (ICEA), National Electrical Manufacturing Association (NEMA), and Association of Edison Illuminating Companies (AEIC) have published standards for the various types of power cables.

12.2 Conductor

Common among all classes in function is the central conductor, the purpose of which is to conduct power (current and voltage) to serve a load. The metals of choice are either copper or aluminum. This central conductor may be composed of a single element (solid) or composed of multiple elements (stranded), on the basis of a geometric progression of 6, 12, 18, etc. of individual strands for each layer. Each layer is helically applied in the opposite direction of the underlying layer.

There are three common types of stranding available.

1. Concentric round
2. Compressed round (97% of the diameter of concentric)
3. Compact round (90–91% of the diameter of concentric)

Note: Some types of connectors may be suitable for stranded types 1 and 2 but not type 3 for the same size.

To improve manufacturing, 19 wire combination unilay stranding (helically applied in one direction one operation) has become popular in low-voltage applications, where some of the outer strands are of a smaller diameter, but the same outside diameter as compressed round is retained. Another stranding method which retains the same overall diameter is single input wire (SIW) compressed, which can be used to produce a wide range of conductors using a smaller range of the individual strands.

Conductors used at transmission voltages may have exotic stranding to reduce the voltage stress.

Cables requiring greater flexibility such as portable power cable utilize very fine strands with a rope type stranding.

Typical sizes for power conductors are #6 American Wire Gage (AWG) through 1000 kcmils. One cmil is defined as the area of a circle having a diameter of one mil (0.0001 in.). Solid conductors are usually limited to a maximum of #1/0 because of flexibility.

The metal type and size determines the ampacity and losses (I^2R). Copper having a higher intrinsic conductivity will have a greater ampacity and lower resistance than an equivalent size aluminum conductor. Aluminum 1350 alloy medium hardness is typical for power cable use.

12.3 Insulation

In order to install power cables underground, the conductor must be insulated. For low-voltage applications, a layer of insulation is extruded onto the conductor. Many types of insulation compounds have been used from natural or synthetic rubber, polyvinyl chloride (PVC), high molecular weight polyethylene (HMWPE), and cross-linked polyethylene (XLPE) to name a few. Although each insulation type has various characteristics, operating temperature and durability are probably the most important. XLPE is probably the most widely used insulation for low-voltage cables. XLPE is a thermoset plastic with its hydrocarbon molecular chains cross-linked. Cross-linking is a curing process, which occurs under heat and pressure, or as used for low-voltage cables, moisture and allows an operating temperature of 90°C.

Multiple layer cable insulation composed of a softer compound under a harder compound, a single layer harder insulation, or a self-healing insulation are used to address protection of the conductor, typically for direct buried low-voltage power cables.

12.4 Medium- and High-Voltage Power Cables

Medium- and high-voltage power cables, in addition to being insulated, are shielded to contain and evenly distribute the electric field within the insulation.

The components and function of a medium- and high-voltage cable are as follows (Figs. 12.2A and 12.2B):

1. The center conductor—metallic path to carry power.
2. The conductor shield—a semiconducting layer placed over the conductor to provide a smooth conducting cylinder around the conductor. Typical of today's cables, this layer is a semiconducting plastic, polymer with a carbon filler, extruded directly over the conductor. This layer represents a very smooth surface, which, because of direct contact with the conductor, is elevated to the applied voltage on the conductor.
3. The insulation—a high dielectric material to isolate the conductor. The two basic types used today are XLPE or ethylene propylene rubber (EPR). Because of an aging effect known as treeing (Fig. 12.3), on the basis of its visual appearance, caused by moisture in the presence of an electric field, a modified version of XLPE designated tree retardant (TRXLPE) has replaced the use of XLPE for medium-voltage applications. High-voltage transmission cables still utilize XLPE, but they usually have a moisture barrier. TRXLPE is a very low loss dielectric that is reasonably

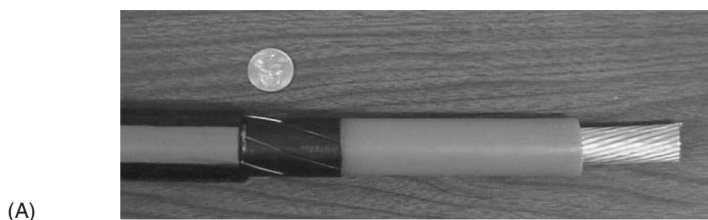
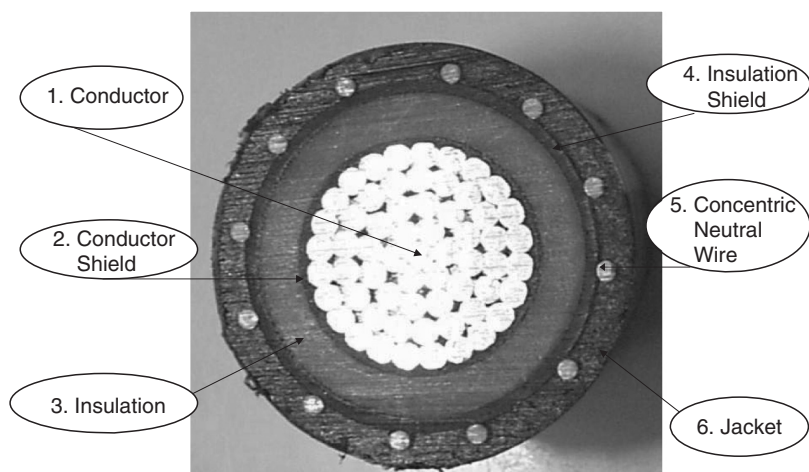


FIGURE 12.2 (A) Medium-voltage cable components, (B) high-voltage cable components.

flexible and has an operating temperature limit of 90°C or 105°C depending on type. TRXLPE because it is cross-linked, does not melt at high operating temperatures but softens. EPR is a rubber-based insulation having higher losses than TRXLPE and is very flexible and has an operating temperature limit of 105°C. EPR does not melt or soften as much as TRXLPE at high operating temperatures, because of its high filler content.

4. The insulation shield—a semiconducting layer to provide a smooth cylinder around the outside surface of the insulation. Typical shield compound is a polymer with a carbon filler that is extruded directly over the insulation. This layer, for medium-voltage applications, is not fully



FIGURE 12.3 Tree in XLPE.

bonded to the insulation (strippable) to allow relatively easy removal for the installation of cable accessories. Transmission cables have this layer bonded to the insulation, which requires shaving tools to remove.

5. The metallic shield—a metallic layer, which may be composed of wires, tapes, or corrugated tube. This shield is connected to the ground, which keeps the insulation shield at ground potential and provides a return path for fault current. Medium-voltage cables can utilize the metallic shield as the neutral return conductor if sized accordingly. Typical metallic shield sizing criteria:
 - A. Equal in ampacity to the central conductor for one phase applications.
 - B. One-third the ampacity for three-phase applications.
 - C. Fault duty for three-phase feeders and transmission applications.
6. Overall jacket—a plastic layer applied over the metallic shield for physical protection. This polymer layer may be extruded as a loose tube or directly over the metallic shield (encapsulated). Although both provide physical protection, the encapsulated jacket removes the space present in a loose tube design, which may allow longitudinal water migration. The typical compound used for jackets is linear low density polyethylene (LLDPE), because of its ruggedness and relatively low water vapor transmission rate. Jackets can be specified insulating (most common) or semiconducting (when jointly buried and randomly laid with communication cables).
7. Moisture barrier—a sealed metallic barrier applied either over or under the overall jacket. Typically used for transmission cables, this barrier may be a sealed tape, corrugated tube, or lead sheath.

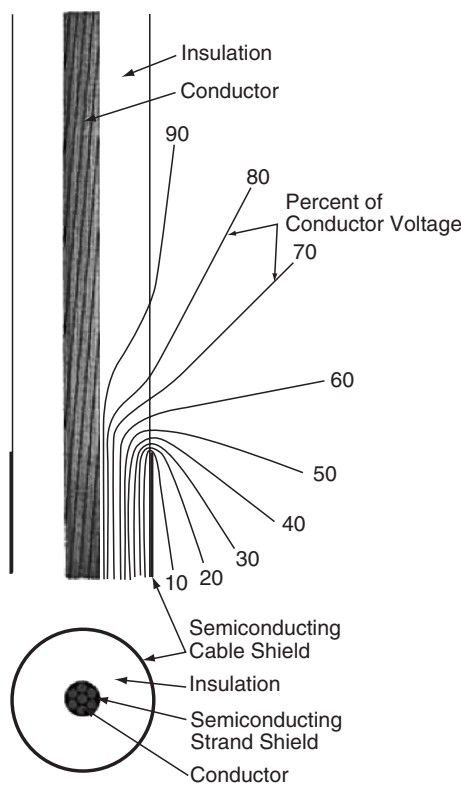


FIGURE 12.4 Voltage distribution in the insulation with the cable shield removed.

Cable components 1–4 comprise the cable core, which in cross-section, is a capacitor with the conductor shield and insulation shield making up the plates on each side of a dielectric. These plates evenly distribute the electric field radially in all directions within the insulation; however, until the metallic shield is added and effectively grounded, the insulation shield is subject to capacitive charging and presents a shock hazard. To be considered effectively grounded, the National Electrical Safety Code (NESC) requires a minimum of four ground connections per mile of line or eight grounds per mile when jointly buried with communication cables for insulating jackets. Semi-conducting jackets are considered grounded when in contact with earth.

Because medium- and high-voltage cables are shielded, special methods are required to connect them to devices or other cables. Since the insulation shield is conductive and effectively grounded, it must be carefully removed a specific distance from the conductor end, on the basis of the operating voltage. Once the insulation shield has been removed, the electric field will no longer be contained within the insulation and the highest electrical stress will be concentrated at the end of the insulation shield (Fig. 12.4). Premolded, cold or heat shrink, or special tapes are applied at this location to control this stress, allowing the cable to be connected to various devices (Fig. 12.5).

12.5 Shield Bonding Practice

Generally, the metallic shields on distribution circuits are grounded at every device. Transmission circuits, however, may use one of the following configurations.

Multiple ground connections (multigrounded) (Fig. 12.6A): The metallic shield will carry an induced current because they surround the alternating current in the central conductor. This circulating current results in an I^2R heating loss, which adversely affects the ampacity of the cable.

Single point grounded (Fig. 12.6B): The metallic shield is grounded at a single point and no current can flow in the metallic shield because there is no closed circuit. This configuration allows the maximum ampacity rating for the cable; however, a voltage will be present on the open end, which may be a hazard. This voltage is dependent on the cable spacing, current, and cable length.

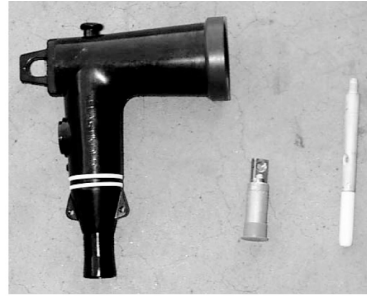
Cross-bonding (Fig. 12.6C): The three-phase circuit is divided into three equal segments. The metallic shield between each segment is connected to an adjacent phase using insulated conductor. Splices at these segments must interrupt the insulation shield to be effective.

12.6 Installation Practice

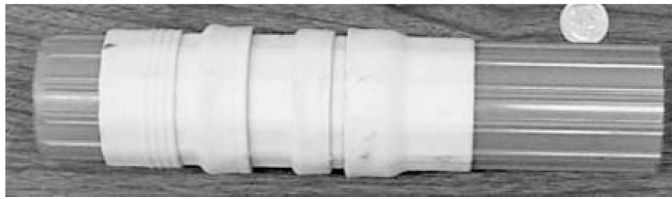
When cables are directly buried in earth, the trench bottom may require bedding sand or select backfill free from rocks that could damage the cable over time. When the cable is installed in conduit, the pulling tension must be limited so as not to damage the conductor, insulation, or shields. Typical value when using a wire basket grip is 3000 lbs. When the cable is pulled around a bend, the pulling tension results in



Cable Splice



Cable Elbow Termination



Cable Outdoor Termination

FIGURE 12.5 Cable accessories.

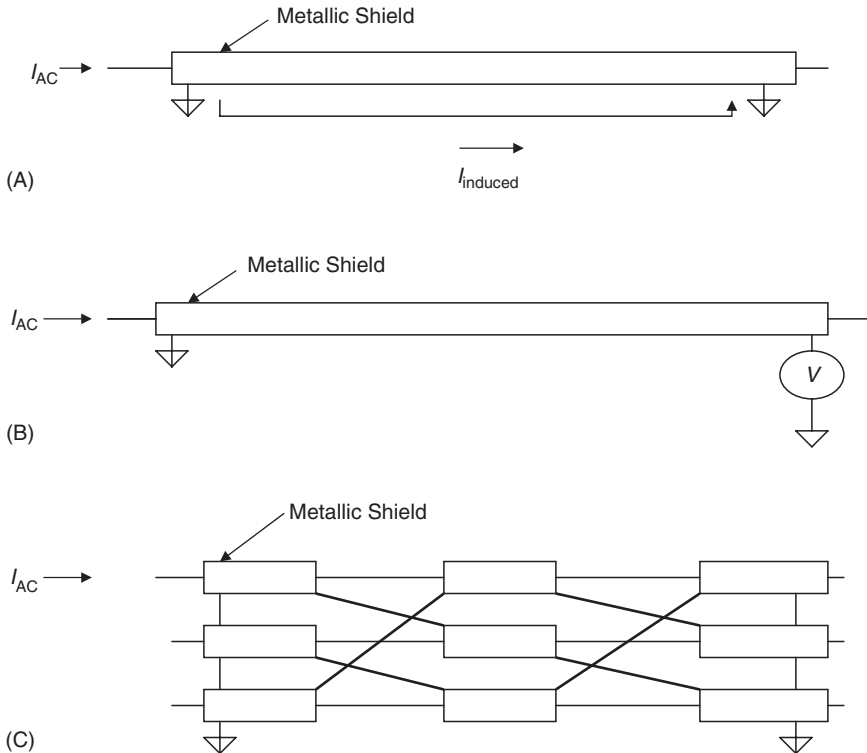


FIGURE 12.6 (A) Multigrounded shield, (B) single point grounded shield, (C) cross-bonding shields.

a side-wall bearing force against the inside surface of the elbow. This force must be limited to avoid crushing the cable components. Cables also have a minimum bending radius limit that prevents distortion of the cable components.

12.7 System Protection Devices

Two types of protecting devices are used on cable systems.

- A. Overcurrent—fuses or circuit breakers. These devices isolate the cable from its source, preventing the flow of damaging levels of current during an overload, or remove a faulted cable from the system allowing restoration of the unfaulted parts.
- B. Overvoltage—surge arrester. This device prevents damaging overvoltages caused by lightning or switching surges from entering the cable by clamping the voltage to a level tolerated by the cable insulation.

12.8 Common Calculations used with Cable

Inductance

$$L_{\text{cable}} = \frac{\mu_o}{2\pi} \left(\ln \left(\frac{2s_{\text{cable}}}{d} \right) + \frac{1}{4} \right) \quad \mu_o = 4\pi 10^{-7} \frac{\text{H}}{\text{m}},$$

where s_{cable} = center-to-center conductor spacing
for three single cables s_{cable} = cube root of each conductor spacing
 d = conductor diameter
 μ_o = permeability of free space

Inductive reactance

$$X_{\text{cable}} = \omega L_{\text{cable}} L \quad \omega = 2\pi f,$$

where f = frequency
 L_{cable} = inductance
 L = length

Capacitance

$$C_{\text{cable}} = \frac{2\pi\epsilon_o\epsilon}{\ln\left(\frac{D}{d}\right)} \quad \epsilon_o = \frac{10^{-9}}{36\pi} \frac{\text{F}}{\text{m}},$$

where ϵ = relative dielectric constant of the insulation (2.4 – XLPE, 2.9 – EPR)
 ϵ_o = free space permittivity
 D = diameter of insulation under insulation shield when present
 d = diameter of the conductor in inches over the conductor shield when present

Charging current

$$I_{\text{cap}} = V_n(\omega C_{\text{cable}} L),$$

where C_{cable} = capacitance
 V_n = voltage line to neutral
 L = length

Ampacity

$$I_{\text{amp}} = \sqrt{\frac{T_c - T_a}{R_{\text{ac}} R_{\text{th}}}},$$

where T_c = conductor temperature

T_a = ambient temperature

R_{ac} = AC resistance at the operating temperature

R_{th} = thermal resistance of surrounding environment

Voltage drop

$$\text{Voltage drop} = I_{\text{cable}}(R_{\text{cable}} \cos(\phi) + X_{\text{cable}} \sin(\phi)),$$

where I_{cable} = current in conductor

R_{cable} = total ac resistance of the cable

X_{cable} = total ac reactance of the cable

ϕ = phase angle between supply voltage and current

For single-phase calculations the values of the main and the return conductors must be used.

Pulling tension single cable in straight conduit

$$T = \mu WL,$$

where μ = coefficient of dynamic friction (0.2–0.7 dependent on cable exterior and type of conduit)

W = cable weight per unit length

L = length

Pulling tension single cable through conduit bend

$$T_{\text{out}} = T_{\text{in}} e^{\mu\phi} \text{ (pounds)},$$

where T_{in} = the tension entering the bend

μ = coefficient of dynamic friction (0.2–0.7 dependent on cable exterior and type of conduit)

ϕ = bend angle in radians

The pulling tensions of each segment of the conduit path are added together to determine the total pulling tension.

When multiple single cables are installed in a conduit, a multiplier must be applied to the cable weight, accounting for configuration as follows:

For three cables with a triangular configuration the weight multiplier is

$$W_{\text{multiplier triangular}} = \frac{2}{\sqrt{1 - \left(\frac{d}{D-d}\right)^2}}.$$

For three cables with a cradled configuration

$$W_{\text{multiplier cradled}} = 1 + \frac{4}{3} \left(\frac{d}{D-d}\right)^2,$$

where d = single cable outside diameter

D = conduit inside diameter.

General References

- Aluminum Electrical Conductor Handbook*, edited by Mark Walker, The Aluminum Association, 1982.
- ANSI/IEEE 575-1988, IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths.
- Association of Edison Illuminating Companies, AEIC.
- CS8-05, Specification for Extruded Dielectric, Shielded Power Cables Rated 5 through 46 kV.
- IEEE 404-1993, IEEE Standard for Cable Joints for use with Extruded Dielectric Cable Rated 5000–138,000 V and Cable Joints for use with Laminated Dielectric Cable Rated 2500–500,000 V.
- IEEE 48-1996, IEEE Standard Test Procedures and Requirements for Alternating Current Cable Terminations 2.5 kV through 765 kV.
- IEEE 1215-2001, IEEE Guide for the Application of Separable Insulated Connectors.
- IEEE 386-2005, IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems above 600 V.
- Insulated Cable Engineering Association, ICEA standards.
- P-53-426, Ampacities, 15–69 kV 1/c Power Cable Including Effect of Shield Losses (Solid Dielectric).
- S-81-570-2005, 600 Volt Rated Cables of Ruggedized Design for Direct Burial Installations as Single Conductors or Assemblies of Single Conductors.
- S-94-694-2004, Concentric Neutral Cables Rated 5 through 46 kV.
- S-97-682-2000, Utility Shielded Power Cables Rated 5 through 46 kV.
- S-105-692-2004, 600 Volt Single layer Thermoset Insulated Utility Underground Distribution Cables.
- S-108-720-2004, Extruded Insulation Power Cables Rated above 46 through 345 kV.
- Southwire Company Power Cable Manual*, Second edition, edited by Thomas P. Arnold, Southwire Company, 1997.